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EFFECTS OF LOAD DISTRIBUTIONS AND AXLE AND TIRE CONFIGURATIONS ON PAVEMENT FATIGUE

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16. Abstract

Damage factor relationships for axle and tire configurations are presented. Adjustment factors are provided to account for variations in load distributions within axle groups, distances between axles of a tandem, and variations in tire pressure for both dual and flotation tire configurations.

Properly accounting for accumulated fatigue of a pavement requires an accurate measure of traffic volume, proportions of vehicle styles (classifications) within the traffic stream, dates of service, estimate of the average damage factor for each classification, and estimate of the tire contact pressure. Weigh-in-motion equipment in its current form provides all of the above ingredients except for the tire contact pressure. A survey of tire pressures may be made and an average calculated to obtain a rough estimate of the effects of loads concentrated on a smaller area than assumed in the past. Such data described above may be used to determine trends in the use of vehicle styles as well as changes in truck volumes and load distributions.

Adjusting for actual conditions of usage may indicate a pavement design thought to last 20 years may last only 14 to 16 years. Such findings affect both new pavement designs and rehabilitation strategies with accompanying effects upon fiscal plans and policies. Adjusted design EALs might require a different pavement template for new designs and a resulting change in costs. Likewise, rehabilitation strategies may change, for example, from a simple overlay to milling and overlay or to complete rehabilitaion because of overhead clearance problems, involving additional costs for shoulder paving and replacement or resetting of guard rails, etc. Therefore, estimating EAL requirements may be far more significant and important than previously recognized. Efforts should include the best method to determine the most accurate fatigue history possible.

All adjustment factors presented are based on the analyses of a limited number of structures and should be used with caution. The accuracy of these analyses are not in question, but the range of structures investigated was limited. They are intended to indicate the trend, shape, and sensitivity of various inter-relationships and their relative magnitudes. Modifications may have to be made upon the analyses of additional pavement structures. Kentucky traffic may differ from that in other areas in the United States, both in types of vehicles in the traffic stream and the type and direction cargo is being transported.

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INTRODUCTION

If it were feasible and practical to manufacture highway truck-trains having perfect cornering and guidance capabilities in the trailing axles, bulk raw materials, such as ores, coals, logs, and freight, could be transported on the highways more efficiently than by some simpler styles of trucks presently used and presently being overloaded by some owners or operators. The notion of truck-trains issue from the "centipede concept" that fostered railroads and freight trains. These concepts should be, and perhaps are being, considered by automotive designers and manufacturers of trucks. Inputs to the vehicle design process may take the form of comparative analyses of damage factors and optimization of tire-and-axle sizes and configurations.

Flexible pavement designs for heavy loads are primarily a function of traffic volume, material characteristics, and the relative damage caused by various load configurations. If material characteristics and traffic volume are assumed to have been determined, variations in thicknesses would be a function of relative damage factors, i.e., the loading conditions. The effects revealed by analyses are specific for flexible pavements, and further analyses of effects upon bridges need to be performed. Analyses presented in this paper are predicated upon the concept of strain energy density exerted by the pavement to resist the loadings. Strain energy is the work done internally by the body and is equal to and opposite in direction to the work done upon the body by the external force. Strain energy is the integral of strain energy density.

This paper presents recent advances in pavement research in the area of magnitudes of loadings, tire and axle configurations, effects of tire pressures and/or contact pressures upon damage factors, and use of traffic data obtained by conventional methods and equipment or by weigh-in-motion equipment.

STRAIN ENERGY DENSITY

Sokolnikoff's Equation 26.8 (1) defined strain energy as

$$U = \int_{\tau} W d \qquad 1$$

in which τ = a stress component,
W = volume density of strain energy at a specific point in the pavement structure, strain energy density, or the elastic potential, and
U = strain energy of the body.

This relationship may be expanded to yield his Equation 26.16 as follows:

$$W = (1/2)\lambda \vartheta e + G\, e_{ij}\, e_{ij} \qquad 2$$

$$= (1/2)\lambda \vartheta^2 + G\,(e_{11}^2 + e_{22}^2 + e_{33}^2 + 2e_{12}^2 + 2e_{23}^2 + 2e_{13}^2),$$

in which e_{ii} = the strain component in the ii direction,
= $e_{11} + e_{22} + e_{33}$,
λ = $E_y\mu/(1+\mu)(1-2\mu)$,
Ey = Young's modulus of elasticity of the material,
μ = Poisson's ratio, and
G = $E_y/2(1+\mu)$, the modulus of rigidity, or the shear modulus.

Young's modulus, Ey, and Poisson's ratio, μ, are input values to the Chevron N-layer computer program (2); the strain components, e_{ii} etc., are outputs of the program.

Noting that Young's modulus, Ey, and the fraction, 1/2, are present in each term of Equation 2,

$$e_W = (2W/E_y)^{1/2} \qquad 3$$

in which e_W = "work strain" and has the same order of magnitude as the strain components e_{ii}.

Since the strain components and the sum of the principle strains are squared, taking the square root as in Equation 4 eliminates any direction and identification as tension or compression. Thus, e_W may be used only as an indicator of the total effect of all strain components.

Stress components may be used to calculate W by Sokolnikoff's Equation 26.17 (1):

$$W = \mu\psi^2/2E_y + (1+\mu)(\tau_{11}^2 + \tau_{22}^2 + \tau_{33}^2)/2E_y + (1+\mu)$$
$$(2 \quad + 2 \quad + 2 \quad)/2E_y \qquad 4$$

in which $\psi = \tau_{11} + \tau_{22} + \tau_{33}$ and
τ_{ii} = stress component in the ii direction.

Noting that $W = (1/2)e_W^2 E_y$ and $W = \tau_W^2/2E_y$, then

$$e_W^2 E_y/2 = \tau_W^2/2E_y \qquad 5$$

in which τ_W = "work stress".

Solving for Ey,

$$E_y = (\tau_W/e_W) \qquad 6$$

Work stress is given by

$$\tau_W = e_W E_y. \qquad 7$$

Squaring the stresses and taking the square root of a summation eliminates, as before, any direction and identification as tension or compression. Figure 1 shows the direct correlation between the tensile strain component at the bottom of the asphaltic concrete layer and work strain.

The Chevron N-layer (2) program was modified to perform the strain energy density calculations for specified depths and radial distances from the center of the load. Computations were requested for the bottom fiber of the asphaltic concrete and the top fiber of the subgrade.

Superposition principles (1) apply when deflections, stresses, and strains are sufficiently small so as not to substantially affect the action of external forces. The nine, basic superposition equations are summarized in Figure 2. For the analyses reported in this paper, the input format to the Chevron N-layer program was modified so loads and desired locations for computations are read in terms of a X-Y-Z coordinate system, and all stresses and strains are resolved and compatible with the coordinate system.

COMPUTATIONAL SCHEME

The Chevron N-layer computer program was used to analyze the effects on highway pavement performance of tire and axle configurations where all tires in a configuration were equally loaded. The load for each individual tire in each axle configuration was varied from 2 kips (8.9 kN) to 8 kips (35.6 kN) on 0.5-kip (2.2-kN) increments. At the AASHO Road Test, there were 100 possible combinations of layer thicknesses, of which 67 were constructed. All 100 possible combinations of layer thicknesses were used in the computer analyses to obtain fatigue relationships between damage factor and total load on various axle configurations. Thicknesses of asphaltic concrete ranged from 2 inches (51 mm) to 6 inches (152 mm) on 1-inch (25-mm) increments. Base thicknesses ranged from 0 to 9 inches (0 to 229 mm) on 3-inch (76-mm) increments, and subbase thicknesses ranged from 0 to 16 inches (0 to 406 mm) on 4-inch (102-mm) increments. An 18-kip (80-kN) four-tired single axleload was applied to each of the 100 structures as the reference condition.

The relationship shown in (Figure 1) between tensile strain at the bottom of the asphaltic concrete and "work strain" is defined by

$$\log(e_a) = 1.1483 \log(e_w) - 0.1638 \qquad 8$$

in which e_a = tensile strain at the bottom of the asphaltic concrete.

The relationship between tensile strain at the bottom of the asphaltic concrete with repetitions of load (3) was converted to a relationship between work strain (4) and repetitions at the bottom of the asphaltic concrete layer by

$$\log(N) = (\log(e_w) + 2.6777807) / -0.15471249 \qquad 9$$

in which N = repetitions.

The damage factor is defined by

$$DF = N18 / NL \qquad 10$$

in which DF = damage factor,
N18 = repetitions calculated by Equation 9 in which the work strain is that due to an 18-kip (80-kN) four-tired single axleload, and
NL = repetitions calculated by Equation 9 in which the work strain is that due to the total load on the axle or group of axles.

Figure 3 shows the relationships between damage factor and total load on axlegroups when the load is uniformly distributed amongst the axles of the group. The curves shown in Figure 3 may be approximated by

$$\log(DF) = a + b(\log(Load)) + c(\log(Load))^2 \qquad 11$$

in which DF = damage factor of total load on axle configuration relative to an 18-kip (80-kN) four-tired axleload,
Load = axleload in kips, and
a, b, c = regression coefficients.

Values for the coefficients were obtained by regression analyses and are summarized in Table 1 (4).

UNEVEN LOADS ON TANDEMS

The effects of uneven load distributions on the axles of a 36-kip (160-kN) tandem group were investigated using those structures shown in Table 2. Analyses revealed that the damage factor for the load distributed evenly on the 36-kip (160-kN) tandem should be adjusted by a multiplicative factor illustrated in Figure 4 (4) and defined by

$$\log(MF) = 0.0018635439 + 0.0242188935(\text{percent}) - 0.0000906996(\text{percent})^2 \qquad 12$$

in which MF = factor to multiply the damage factor given in Equation 11 to adjust the fatigue for an uneven load distribution and
percent = |(Axleload No. 1 - Axleload No. 2)| x 100/ (Axleload No. 1 + Axleload No. 2).

An analysis of the first 670 tandem axleload distributions given in the 1980 W-4 tables for Kentucky indicated a 40-percent increase in the calculated fatigue when the uneven load distribution was considered.

UNEVEN LOADS ON TRIDEMS

The increased use of tridem axle groups on trucks suggested an investigation of actual load distributions. Inspection of the W-4 table revealed that the majority of tridems had uneven load distributions. A study was initiated to develop adjustment factors to account for those uneven load distributions and the various patterns of uneven loadings.

Structures given in Table 2 were used in the analyses. The total load was kept constant at 54 kips (240 kN). Table 3 summarizes the combinations of individual axleloads used to equal the constant total load. Five basic patterns of load distributions were investigated. Considering patterns that were mirror images of one of the five and that two of the axles might be equally loaded, there were 13 combinations. The following definitions were used:

M = the heaviest axleload of the three axles,
L = the least axleload of the three axles,
I = the intermediate axleload between the maximum and minimum axleload, and
E = the axleload is equal to an axleload on at least one other axle.

Equations 9 and 10 provide the basis for calculating damage factors. The Chevron N-layer computer program was used to calculate work strain. The location producing the severest damage factor occurs at the edge of the inside tire closest to the outside tire of the dual. This is the same location used to calculate damage factor relationships using Equations 9 and 10 that result in the equations shown in Table 1 and Figure 3. Each load pattern in Table 3 was subjected to analyses by the Chevron N-layer computer program and the allowable repetitions associated with 54 kips (240 kN) uniformily distributed on the tridem were determined.

Since Table 1 contains the equation for an evenly distributed load on the tridem, only four basic patterns remained to be analyzed. Figure 5 shows the results of the regression on all data without regard to load pattern. Table 4 summarizes the coefficients and regression statistics for Figure 5. The influence of structure upon the scatter of data as the result of uneven loading within the tridem was very significant, but structure was not nearly so influential for an uneven load distribution within a tandem. For 670 tandems (2), the accumulated adjusted EAL was 1.4 times that of an evenly distributed load. For 1,951 tridems, the accumulated adjusted EAL was 2.3 times that of evenly distributed loads.

Tridem axleload distributions (5) were subjected to analysis by the equations shown in Table 4. One group of 1,055 tridems were on single-frame trucks that probably were either dump trucks or tractors of semi-trailer trucks. A second group of 896 tridems were on the semi-trailers. The actual pattern of load was associated with its respective equation and also the equation fitted to all load patterns. Table 5 is a summary of all tridems.

The accumulated adjusted EAL by the respective load pattern was 2.9 (from Table 6) times larger than if the same total loads had been uniformily distributed within the tridem. This compares with 1.9 (from Table 7) for tridems on trailers and 2.5 without regard to location of the tridem on the truck (Table 5). The accumulated adjusted EAL without regard to load pattern was 2.6

(from Table 6) times larger than if the same total loads had been evenly distributed. This compares with 1.9 for the tridems on trailers (Table 7) and 2.3 without regard to location of the tridem (Table 5). Included in Table 5 is the number of tridems in each of the thirteen load patterns. Approximately 10 percent of the tridems were actually uniformly loaded. There were an additional 66 tridems in which axle weights differed by 0.1 kip (0.44 kN) or less. Thus, for 13.9 percent of the tridems, the load could be considered to be uniformily distributed. It appeared the tridems on the trailer were more likely to be evenly loaded than those on the tractor. For the tractor, the loads were either equal, within 0.2 kips (0.89 kN) of being equal, or else significantly different from being equal. Table 8 summarizes the percentage of tridems by the relative load on the middle axle. Nearly 18 percent of the middle axles carried the least load within the tridem.

Table 5 also contains the number of tridems for which the load distribution was so extremely uneven that the two lightest axleloads were added together and the group analyzed as an unevenly loaded tandem. Table 5 shows that 19 tridems (approximately 1 percent) analyzed as tandems caused approximately three times the fatigue as 1,937 tridems for which the load was more evenly distributed.

FLOTATION VERSUS DUAL TIRES

In recent years, wide flotation tires have been utilized on steering axles and, more recently, to replace dual tires on rear axles. Ready-mix transit trucks that used to have ten tires on three axles, or fourteen tires on four axles, now may have a total of six, or eight, tires, respectively, with all tires being the same size. To determine the effects of single flotation versus "standard" dual tires, pavement structures shown in Table 2 were analyzed. using the Chevron N-Layer computer program. The loads on each tire ranged from 5.5 kips (24.5 kN) to 9.5 kips (42.3 kN). The total load on the assembly was divided equally and applied to all flotation tires. The response was compared to the response having the same total load using standard dual tire arrangements on the same number of axles. The total work calculated by the Chevron N-layer computer program coupled with a fatigue relationship determined the number of equivalent 18-kip (80- kN) axleloads (EAL's). Damage factors, or load factors, defined by Equations 9 and 10, were calculated for flotation tires on tandem and tridem groups. Figure 6 compares damage factors for the axle assemblies using single flotation or dual tires. There is a larger difference in damage factors between flotation tires and dual tires at lesser loads and the damage factors approach equality with dual tires at the higher loads. Contact areas for flotation tires at higher loads approach the total area of standard dual tires. The bottom portion of Table 10 provides values of the coefficients for Equation 11 for four-tired tandem and six-tired tridem axle assemblies. Analyses have not been made for unequal load distributions on single flotation tires.

EFFECTS OF AXLE SPACING

To determine the sensitivity of damage factor to the distance between axles of a tandem group, a total load of 36 kips (160 kN) was divided equally to all eight tires -- 4.5 kips (40 kN) per tire. Figure 7 illustrates the appropriate relationship between axle spacing and an adjustment factor and is defined as

$$\log(adj) = -1.589745844 + 1.505262618(\log(sp)) -0.3373568476(\log(sp))^2 \qquad 13$$

in which adj = adjustment for axle spacing greater than 54 inches (1.37 m), and
sp = spacing between two axles of tandem, inches.

KINGPIN LOCATION

The kingpin location, the connection between a trailer and the tractor, can be varied by the trucker from zero up to as much as 24 or 30 inches (610 or 762 mm) from its desirable location. Displacements of the kingpin by as much as 18 inches (457 mm) is not uncommon. Such a displacement may tend to shift a portion of the trailer load to the front steering axle of the vehicle where small increases in load are proportionately more damaging to the pavement as well as creating a safety problem by increasing the difficulty of steering.

In August 1978, 129 vehicles of the "332" classification (five-axle semi-trailer truck) were inspected and weighed at a scale on I 64 in Kentucky. Figure 8 shows that the front axleload generally increased as the kingpin assemble was located farther from the center of the tandem. The increase from 9 kips (40 kN) to 10.7 kips (47.6 kN) on the front axle causes the damage factor for that axle to increase from 0.2 to 0.4. However, a 1.7-kip (7.6-kN) increase of the tandem axleload of 34 kips (151.2 kN) causes an increase in the damage factor of only 0.18. Analysis indicates that simply moving the kingpin assembly back to the center of the tandem on the tractor will not increase the pavement life significantly. There is no adjustment factor for location of the kingpin because any shift in position is directly reflected in the axleloads.

TIRE PRESSURES

Extensive analyses of the structures given in Table 2, plus others, indicated the most critical location with regard to shear strains within the pavement was at the bottom of the asphaltic concrete and under the inside dual tire at the edge closest to the end of the axle (nearest the outside dual tire). Also, the computation of strain energy density employs all components of strain, or stress, at that point within the structure.

While investigating an interstate pavement failure, it was deemed desireable to obtain a sample of the axleloads of the truck traffic using that pavement to help recreate the fatigue history. Loadometer data had been obtained during the summer of 1984 at the loadometer station located approximately one mile south (1.6 km) of the pavement under study. Axleloads, tire contact length, tread width, type of tire construction (radial or bias ply), tire pressure, and axle spacing were obtained for 14 trucks. Because tire pressures had been measured at 120 psi (827 kPa) in Texas during 1984 (6), tire pressures also were measured only on the left outside tires of all axles on another 39 trucks. Figure 9 is a histogram summarizing tire pressures data in 5-psi (34-kPa) groups. In summary, the following observations are presented:

1. Seventy-four percent of all tires were radials.
2. Pressure in seven percent of all tires ranged between 120 and 129 psi (827 kPa and 889 kPa).
3. The average tire pressure for all tires was 102 psi (701 kPa).
4. The average tire pressure for all tires on the steering axle was 105 psi (726 kPa).
5. The average tire pressure for all tires on rear axles was 101.4 psi (699 kPa).
6. Pressure for radial tires:
   a. the average for all tires was 105 psi (723 kPa),
   b. the average for the steering axle was 108 psi (743 kPa), and
   c. the average for tires on rear axles was 105 psi
7. Pressure for bias-ply tires:
   a. the average for all tires was 90 psi (617 kPa), and
   b. there was only 0.3-psi (2-kPa) difference in pressure between the steering and rear axle tires .
8. The average pressure in radial tires was 15.3 psi (105 kPa) higher than for bias ply tires.
9. As much as 40 psi (276 kPa) differential was found between tires within the same tandem group. Five flat tires were not included in this analysis.

At the AASHO Road Test, most tires were inflated to 75 psi (517 kPa), resulting in a contact pressure of 67.5 psi (465 kPa). Increased tire pressures decrease the length (and thus area) of the tire in contact with the pavement. The reduced area causes an increased punching effect within the pavement structure. Intuitively, as tire pressures increase, the punching effect will increase and may create a shearing failure surface different from the traditional form of a spiral curve. The Chevron N-layer computer program does not account for punching-type failure.

EFFECTS OF TIRE-PRESSURE VARIATIONS ON PAVEMENT FATIGUE

Structures shown in Table 2 were loaded using an 18-kip (80-kN) four-tired single axleload and analyzed by the Chevron N-layer computer program. The reference condition was defined as a tire inflation pressure of 75 psi (517 kPa), which corresponded to a tire contact pressure of 67.5 psi (465 kPa) (Table 5 of Reference 6) used at the AASHO Road Test. Tire pressures investigated in this analysis were 80 psi (552 kPa), 115 psi (793 kPa), 150 psi (1.03 MPa), and 200 psi (1.38 MPa). Work was calculated at the bottom of the asphaltic concrete layer and under the inside tire at the edge closest to the end of the axle.

All damage factors associated with loads and adjustment factors for variations in load distribution between axles and distance between axles of a tandem have been found to be relatively insensitive to pavement thickness. However, Figure 10 illustrates that the magnitudes of adjustment factors for variations in tire pressures for four-tired single axles are dependent upon the thickness of the asphaltic concrete. Figures 11 and 12 present adjustment factors for variations in tire pressures on eight-tired tandem and twelve-tired tridem axle groups, respectively. In Figures 10-12, it was assumed that all tires were equally loaded. Substituting the terms "adjustment factor" for "damage factor" and "tire pressure" for "load", the form of Equation 12 describes the adjustment factor as a function of tire pressure for a constant thickness of asphaltic concrete. Values for the regression coefficients are given in Tables 9 and 10.

Another analysis was made for axle groupings using flotation tires instead of dual tires. Figures 13 through 15 present adjustment factors as a function of tire pressures for single, tandem, and tridem axle groups. Note that fatigue effects of tire-pressure variations for flotation tires are much more severe (as much as four to five times) as for the same pressure in groups using dual tires.

To illustrate the increased fatigue caused by increased tire pressures, loadometer data obtained during the summer of 1984 at a site on I 65 in Hardin County, Kentucky, was analyzed. The pavement 1 mile (1.6 km) north of the loadometer station consisted of 7 inches (178 mm) of asphaltic concrete over 16 inches (406 mm) of dense-graded aggregate base. For the steering axle, multiplying the inflation pressure by 0.9 (67.5 psi / 75 psi) yields an approximate contact pressure of 95 psi (653 kPa). For all tires on rear axles, the average inflation pressure of 101 psi (699 kPa) was multiplied by 0.9 to obtain an approximate contact pressure of 91 psi (629 kPa). Adjustment factors are shown in Table 11.

Axleload data collected at the loadometer station mentioned above were analyzed by vehicle classification to determine an average damage factor for each axle location and for the total vehicle. Table 12 contains four sets of average damage factors for the vehicle classifications at that loadometer station. The first set of factors were obtained using the AASHTO load equivalencies associated with a structural number of 4.0 and level of serviceability of 2.5. The remaining sets show the result of including more detailed data (additional adjustments for non-reference loading conditions) in determining the damage factors. The effects of the different sets of damage factors will be shown in an example problem. Average damage factors shown in Table 12 were obtained from data taken at one site only, but probably are indicative of comparisons between vehicle classifications.

USING TRAFFIC DATA

Data obtainable from weigh-in-motion systems include

1. individual wheel loads and axleloads,
2. distance between axles,
3. vehicle classification,
4. overall vehicle length, and
5. speed.

Thus, data are available to determine all of the appropriate adjustment factors previously discussed except for tire contact pressure. Contact pressure and tire width might be obtainable if one or more sensors were installed to determine the width of the tire. The time that the tire is in contact with a sensor coupled with data from speed loops would provide data to calculate tire contact pressures. Thus, another major factor influencing the rate of accumulated fatigue would be available.

Weigh-in-motion data provide the necessary ingredients to calculate the damage factor for each vehicle and the average for each vehicle classification. Changes in legal load limits, typical axleloadings, axle and tire arrangements, and use of particular vehicle classifications have resulted in increased damage factors. Knowledge of these changing trends provides the possibility for estimating EAL for both existing and future pavements with greater accuracy and confidence.

Trends in vehicle usage may be evaluated from weigh-in-motion data without the need for manual vehicle classification counts. Estimating the rate of consumption of the remaining pavement life requires knowing trends of vehicle classification usage, magnitudes of loads, and accumulation rates of pavement fatigue.

Analyses of 1984 Kentucky loadometer data yielded the first definitive data for "double-bottom" trucks (tractor, semi-trailer, and full trailer). This combination in Kentucky utilizes two short trailers that together are approximately equal to the length of the traditional semi-trailer. Axleload data for each double-bottom truck were used to calculate the gross load and the total damage factor for that vehicle. A search of the data listing was made for a "332" vehicle (five-axle semi-trailer truck) having the same gross load or within 0.3 kips (1.3 kN), and the damage factor for the "332" was calculated. Thirty-three "double-bottom" trucks were compared to 33 individual "332" trucks with the same gross load. The damage factors for each vehicle type were summed and an average obtained as shown in Table 13. For the 33 pairs, the average damage factor for the "double-bottoms" was 1.74 times greater than the average for the "332" vehicles.

Kentucky vehicle enforcement officers have noticed a marked increase in the number of double-bottom trucks using Kentucky interstate pavements. Further increased use of double-bottom trucks is expected as new short trailers are purchased and placed in service with the accompanying retirement of the traditional long semi-trailer. Knowledge of such trends provides the ability to make proper estimates of future EAL requirements for new pavement designs and/or determining the appropriate pavement rehabilitation strategies.

Weigh-in-motion data provide key elements in the proper evaluation of accumulated EAL and predicting the remaining life of a pavement. However, use of adjustment factors presented herein may be used with the individual vehicle data of loadometer studies to determine the average damage factor per vehicle classification and its variation with time. These relationships combined with data from vehicle classification counts and automatic vehicle counters provide the necessary ingredients to improve the "prediction" of accumulated EAL for given pavements provided the data are analyzed to the fullest extent. Weigh-in-motion equipment will help to improve such estimates.

STEP-BY-STEP PROCEDURE TO CALCULATE DAMAGE FACTORS

The following procedure has been used to calculate accumulated fatigue for the pavement used as a case history in this paper.

1. Damage factor relationships for each combination of axle location and arrangement shown in Figure 4 are defined by Equation 11 and values for the coefficients are summarized in Table 1.
2. Use Equation 12 to compensate for uneven load distribution within a tandem group.
3. Equation 13 defines the relationship for adjusting the damage factor when the distance between the two axles of a tandem is greater than 54 inches (1.37 meters).
4. To adjust for uneven load distribution amongst the three axles of a tridem, use the equation at the top of Table 4 with the values for the coefficients listed under "All Patters Above".
5. Multiply 0.9 times the tire inflation pressure to adjust tire inflation pressure to tire contact pressure. Insert tire contact pressure into the equation at the top of Tables 9 and/or 10 with the values for the coefficients listed below that are appropriate for the number of tires per axle (Table 9 or 10) and the number of axles within the group.
6. Sum the damage factors for each axle location for each vehicle classification -- sum all calculated damage factors for the steering axles and obtain an average of the steering axle. Repeat for each group of axles to obtain the average for each group of axles. Such calculations give insight into the load carrying efficiency by location of axles.
7. For each vehicle classification, damage factors for each axle group may be calculated for each year and when plotted versus time provide the relationship of changing axleloads with time. Thus, each vehicle classification may be evaluated for load carrying efficiency in terms of accumulated pavement fatigue.

CASE HISTORIES

As referred to earlier, it was necessary to recreate an estimated accumulated fatigue history for a particular pavement. Available data included

1. vehicle volumes by hour for each day during the life of the pavement obtained by an automatic traffic recorder,
2. quarterly hand vehicle classification counts, and
3. loadometer studies in 1984 for input to the annual W-4 Tables.

An estimate of traffic volume by vehicle classification was obtained using the ATR and hand classification counts. Loadometer data were analyzed several ways. The simplest procedure involved estimating the load equivalency for each vehicle. All variations in load distribution amongst axles within a group and axle spacing were ignored. Under these assumptions, the data were subjected to analyses using both the Kentucky and AASHTO damage factor relationships. The average damage factor for each vehicle was accumulated for the respective vehicle classification and an average equivalency value obtained for each classification as shown in Table 12. Accumulating the product of vehicle volume and respective average damage factor produced the total accumulated 18-kip (80-kN) equivalent axleloads shown in Table 14.

A second analysis of the loadometer data included adjustments to account for uneven axleloads within the axle group (tandem or tridem) and the effects of increased spacing over 54 inches (1.3 m) within a tandem group. As before, a damage factor for each vehicle was calculated and accumulated within its classification. An average damage factor was calculated for each vehicle classification after all vehicles had been investigated. The total 18-kip (80-kN) equivalent axleloads were obtained for each vehicle classification as the product of the respective classification volume and average load equivalency value.

The third analysis adjusted the damage factors obtained by the second analysis for increased tire contact pressure. Adjustments were made using the factors given in Table 11.

AASHTO damage factors assume that the effects of the steering axle are taken into account through the factors for the rear axles. Those damage factors also assume that all axles in a given assembly are equally loaded. This assumption was valid at the AASHO Road Test because of the careful placement of loads on the trailers. Current data indicate that equal load distributions on the axles within the same group are seldom the case.

Some have used the AASHTO "single axle damage factor relationship" for determining effects of loads on steering axles. Even though this is not the correct procedure, AASHTO damage factors for single axleloads were applied to the steering axles of the above case history. Table 14 contains the comparison of the four methods of calculating pavement fatigue.

To determine a reasonable estimate of the total fatigue damage caused by the front axle, one method of analysis combined the damage factors for the steering axle given in Table 15 with the appropriate vehicle volumes from Table 14. The total accumulated fatigue for the steering axle (Method C in Table 15) was 340,613 18-kip (80-kN) EAL of the total of 845,175 18-kip (80-kN) EAL. Thus, the estimated fatigue associated with the steering axle was 40 percent of the total fatigue caused by all axles. The comparable value using the AASHTO method was 52,976 18-kip (80-kN) EAL, which was eight percent of the total. Thus, a muchly reduced fatigue estimate is obtained for both new pavement thickness designs and for rehabilitation strategies. Data in Table 14 provide a way to compare the different procedures.

The second "case history" involved comparing average damage factors for vehicle classifications using data taken from the 1964 Kentucky W-4 Tables versus the analyses of the 1984 loadometer data on I 65 in Hardin County, as discussed in the case history. The "observed number of vehicles" shown in the 1964 table for each vehicle classification were converted to a percentage. The number of vehicles for the same classifications from the 1984 loadometer data also were converted to percentages (Table 16). Table 17 contains the corresponding average damage factors for the vehicle classifications. The estimated fatigue was obtained as the product of 1 million trucks by the percentages of trucks in each vehicle classification, and the respective average damage factor for each classification. The combination of higher tire contact pressures, heavier axleloads, and changes in use of vehicle styles indicates fatigue calculations for 1984 are 2.50 times greater than for 1964 for the same volume of trucks.

SUMMARY

All adjustment factors presented are based on the analyses of a limited number of structures and should be used with caution. The accuracy of these analyses are not in question, but the range of structures investigated was limited. They are intended to indicate the trend, shape, and sensitivity of various inter-relationships and their relative magnitudes. Modifications may have to be made upon the analyses of additional pavement structures. Kentucky traffic may differ from that in other areas in the United States, both in types of vehicles in the traffic stream and the type and direction cargo is being transported.

Damage factor relationships for axle and tire configurations are presented. Adjustment factors are provided to account for variations in load distributions within axle groups, distances between axles of a tandem, and variations in tire pressure for both dual and flotation tire configurations.

Properly accounting for accumulated fatigue of a pavement requires an accurate measure of traffic volume, proportions of vehicle styles (classifications) within the traffic stream, dates of service, estimate of the average damage factor for each classification, and estimate of the tire contact pressure. Weigh-in-motion equipment in its current form provides all of the above ingredients except for the tire contact pressure. A survey of tire pressures may be made and an average calculated to obtain a rough estimate of the effects of loads concentrated on a smaller area than assumed in the past. Such data described above may be used to determine trends in the use of vehicle styles as well as changes in truck volumes and load distributions.

Adjusting for actual conditions of usage may indicate a pavement design thought to last 20 years may last only 14 to 16 years. Such findings affect both new pavement designs and rehabilitation strategies with accompanying effects upon fiscal plans and policies. Adjusted design EALs might require a different pavement template for new designs and a resulting change in costs. Likewise, rehabilitation strategies may change, for example, from a simple overlay to milling and overlay or to complete rehabilitaion because of overhead clearance problems, involving additional costs for shoulder paving and replacement or resetting of guard rails, etc. Therefore, estimating EAL requirements may be far more significant and important than previously recognized. Efforts should include the best method to determine the most accurate fatigue history possible.

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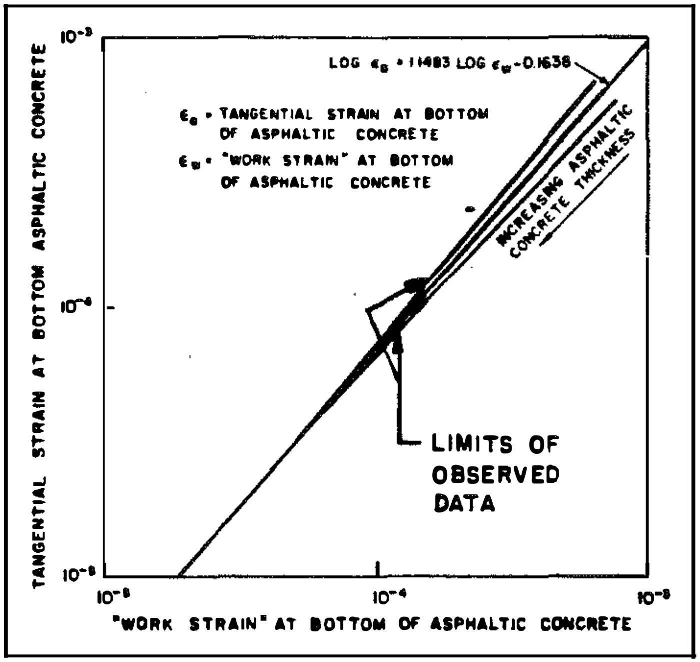
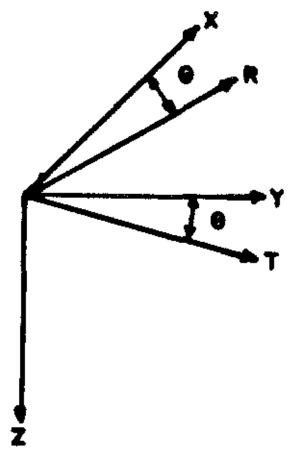


Figure 1. Tensile Strain versus "Work Strain."

SUPERPOSITION EQUATIONS



$$\sigma_x = \sigma_R \cos^2\theta - 2\tau_{RT} \cos\theta \sin\theta + \sigma_T \sin^2\theta$$

$$\tau_{xy} = \sigma_R \cos\theta \sin\theta + \sigma_{RT}(\cos^2\theta - \sin^2\theta) - \sigma_T \sin\theta \cos\theta$$

$$\tau_{xz} = \tau_{RZ} \cos\theta - \tau_{TZ} \sin\theta$$

$$\sigma_y = \sigma_R \sin^2\theta + 2\tau_{RT} \sin\theta \cos\theta + \sigma_T \cos^2\theta$$

$$\tau_{yz} = \tau_{RZ} \sin\theta + \tau_{TZ} \cos\theta$$

$$\sigma_z = \sigma_z$$

$$\tau_{yx} = \tau_{xy}$$
$$\tau_{zx} = \tau_{xz}$$
$$\tau_{zy} = \tau_{yz}$$

Figure 2. Basic Equations by Superposition Principles.

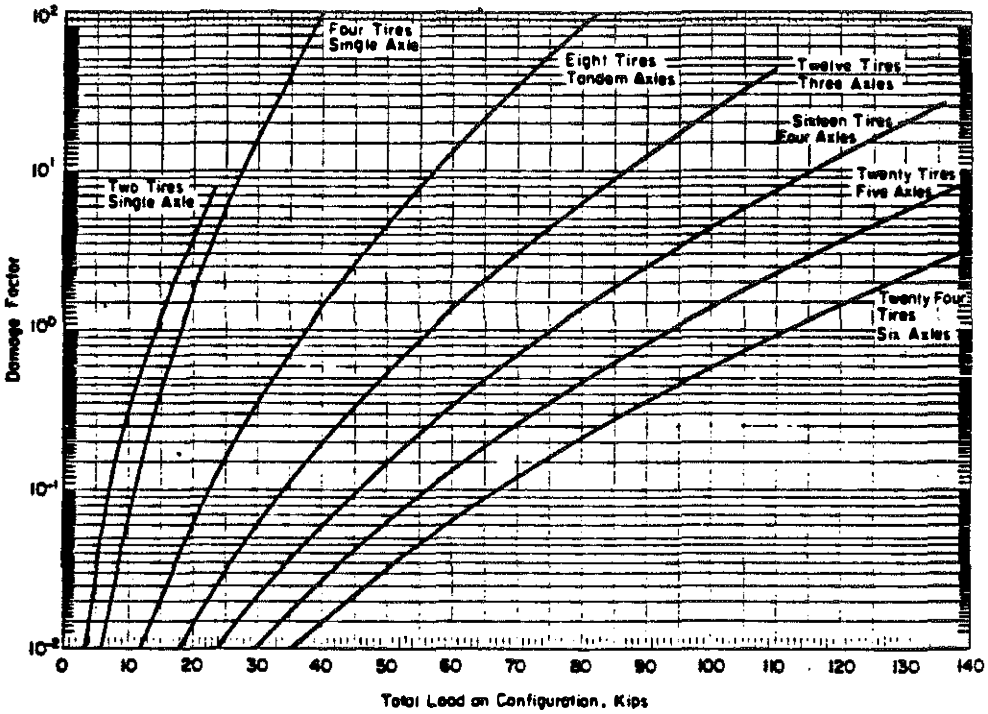


Figure 3. Relationship Between Load Equivalency and Total Load on the Axle Group and Evenly Distributed on All Axles.

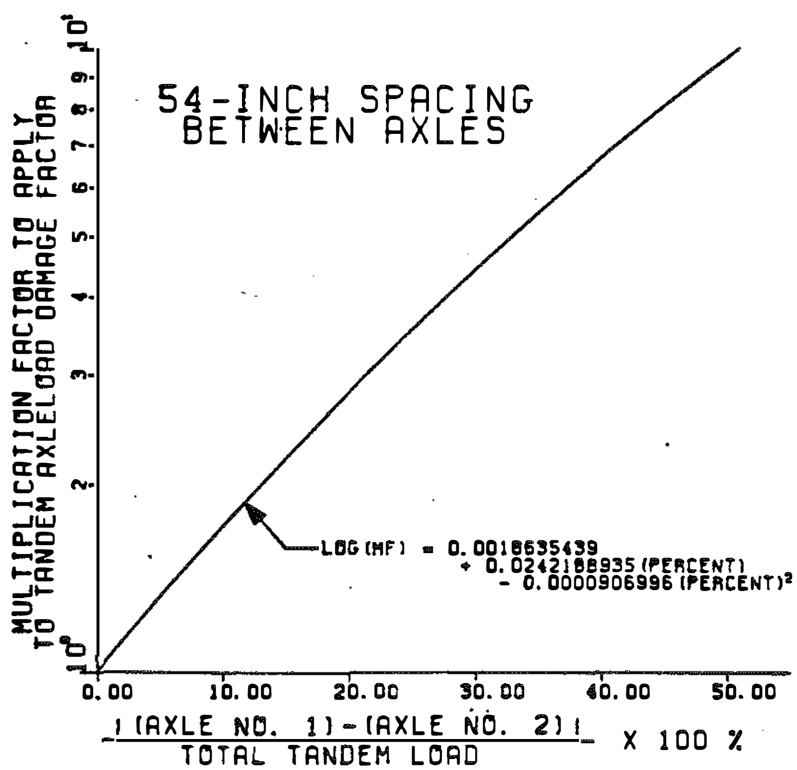


Figure 4. Multiplication Factor to Account for Uneven Load Distribution on the Two Axles of a Tandem.

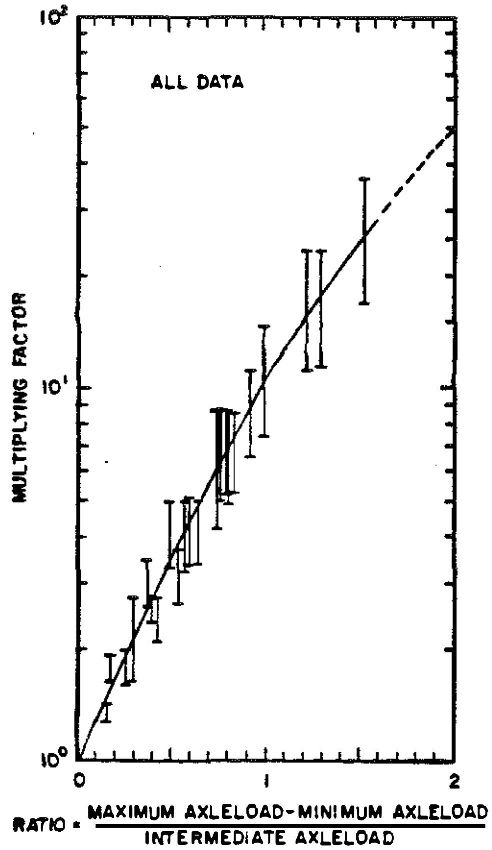


Figure 5. Multiplying Factor for Uneven Load Distribution on the Axles Within the Tridem Without Regard to Location of Maximum or Minimum Axleloads.

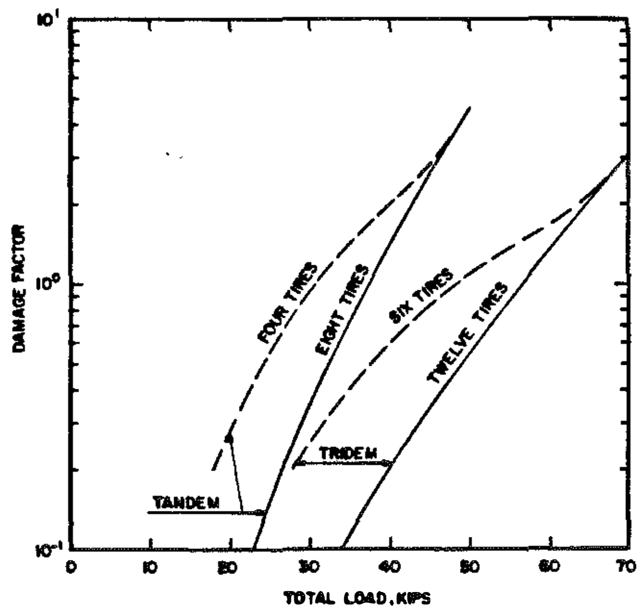


Figure 6. Load-Equivalency Factors Relationships for Four-tired versus Eight-tired Tandem Axles and Six-tired versus Twelve-tired Tridem Axles.

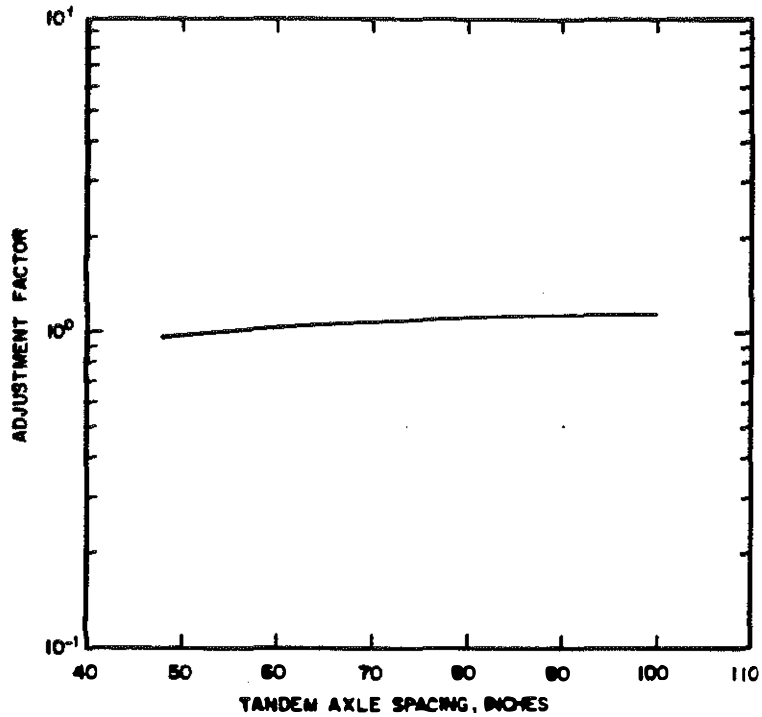


Figure 7. Adjustment Factor to Account for Spacing Between Two Axles of Tandem Group.

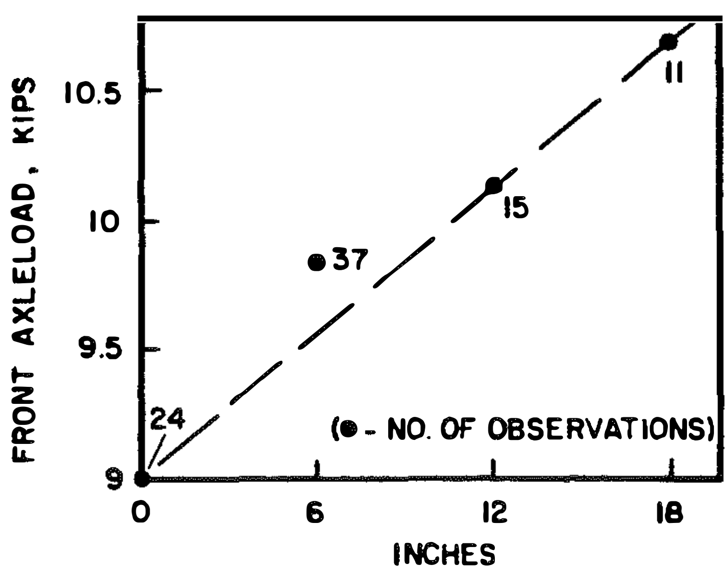


Figure 8. Frônt Axleload versus Position of Kingpin Assemble Relative to the Center of Tractor Tandem.

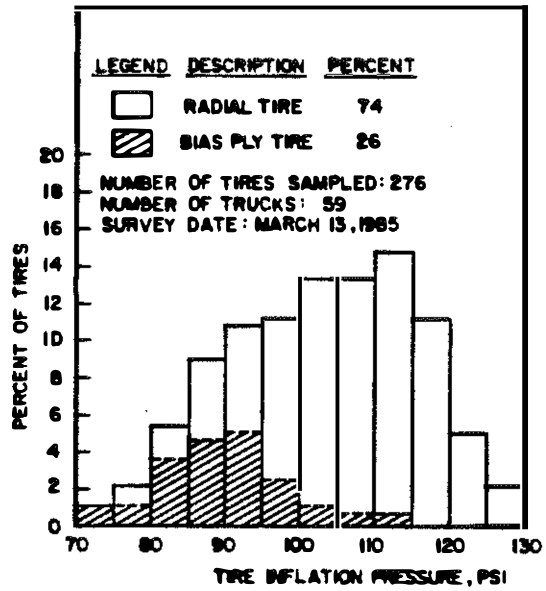


Figure 9. Histogram of Measured Tire Pressures.

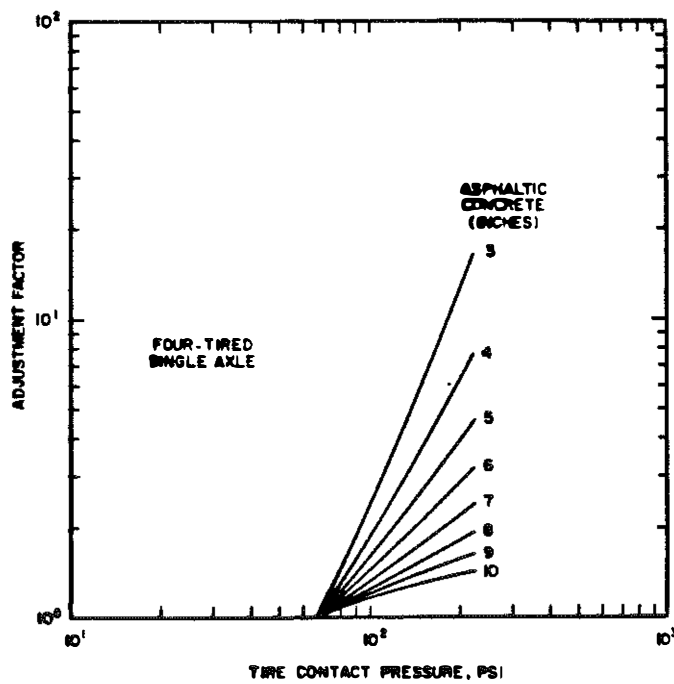


Figure 10. Adjustment Factor versus Tire Contact Pressure for Four-tired Single Axle.

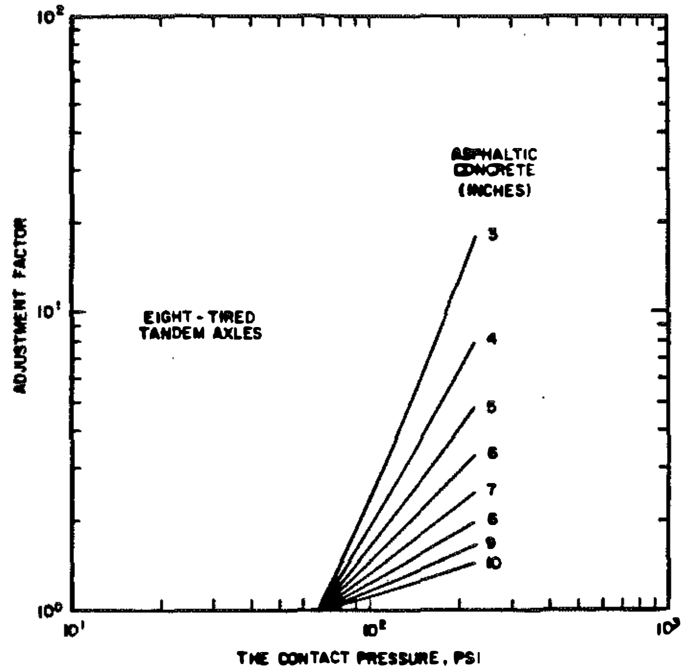


Figure 11. Adjustment Factor versus Tire Contact Pressure for Eight-tired Tandem Axles.

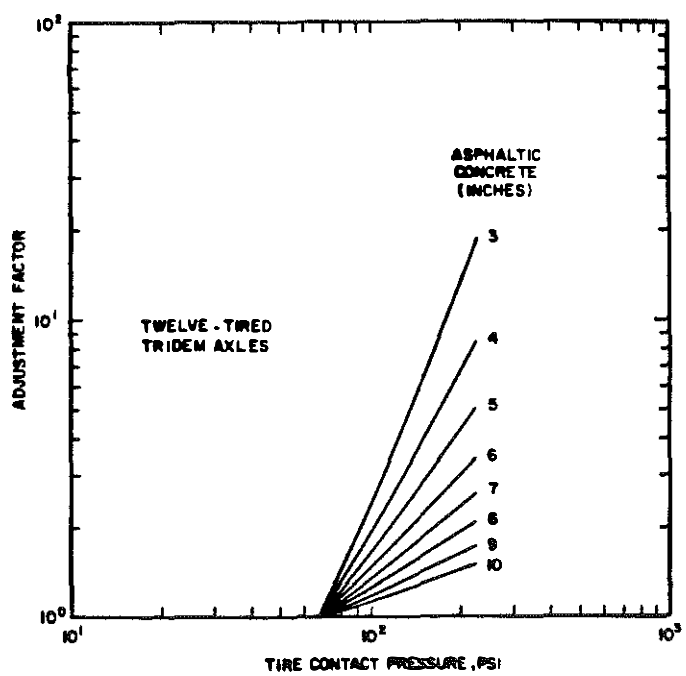


Figure 12. Adjustment Factor versus Tire Contact Pressure for Twelve-tired Tridem Axles.

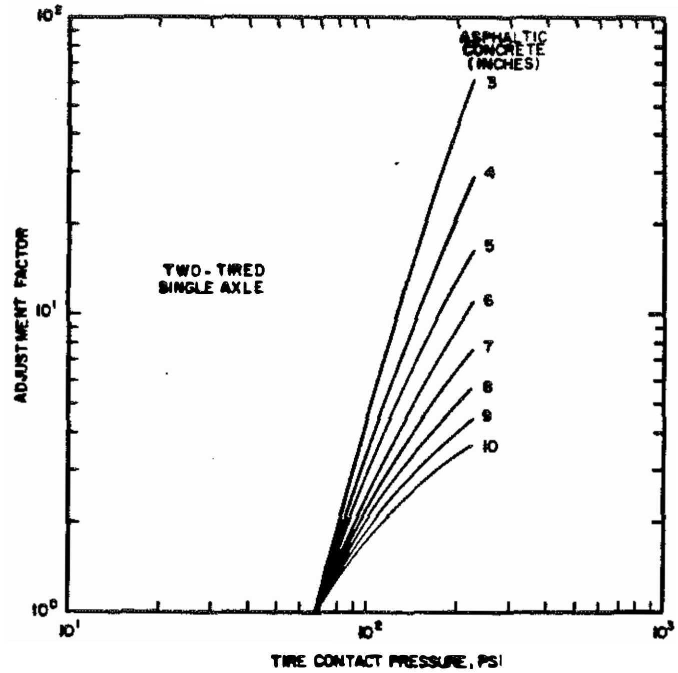


Figure 13. Adjustment Factor versus Tire Contact Pressure for Two-tired Single Axle.

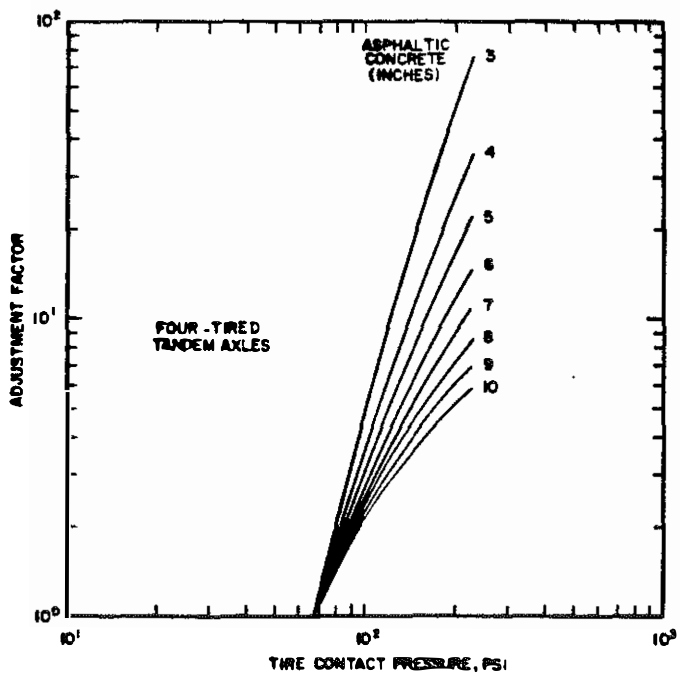


Figure 14. Adjustment Factor versus Tire Contact Pressure for Four-tired Tandem Axles.

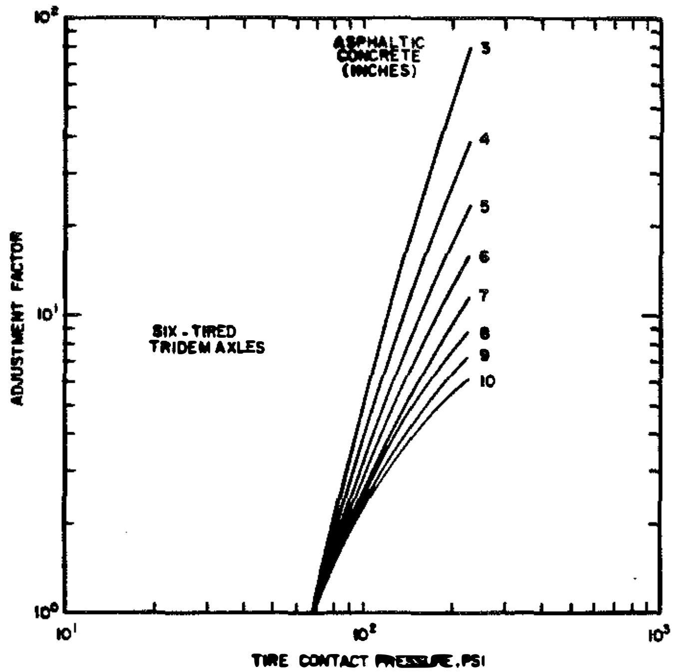


Figure 15. Adjustment Factor versus Tire Contact Pressure for Six-tired Tridem Axles.

TABLE 1. REGRESSION COEFFICIENTS TO CALCULATE DAMAGE FACTORS FOR VARIOUS AXLE CONFIGURATIONS

$$\log(\text{Damage Factor}) = a + b(\log(\text{Load})) + c(\log(\text{Load}))^2$$

AXLE CONFIGURATION	COEFFICIENTS a	b	c
Two-Tired Single Front Axle	-3.540112	2.728860	0.289133
Four-Tired Single Rear Axle	-3.439501	0.423747	1.846657
Eight-Tired Tandem Axle	-2.979479	-1.265144	2.007989
Twelve-Tired Tridem Axle	-2.740987	-1.873428	1.964442
Sixteen-Tired Quad Axle	-2.589482	-2.224981	1.923512
Twenty-Tired Quint Axle	-2.264324	-2.666882	1.937472
Twenty-four Tired Sextet Axle	-2.084883	-2.900445	1.913994

TABLE 2. PAVEMENT STRUCTURES FROM AASHO ROAD TEST USED IN ANALYSES

LAYER THICKNESS, inches: ASPHALTIC CONCRETE	CRUSHED STONE BASE	IMPROVED SUBGRADE	AASHTO STRUCTURAL NUMBER
3	3	8	2.62
4	3	8	3.06
5	3	8	3.50
6	3	8	3.94
3	6	8	3.04
4	6	8	3.48
5	6	8	3.92
6	6	8	4.36

TABLE 3. AXLELOAD DISTRIBUTIONS USED IN INVESTIGATION

	AXLELOAD, kips					
AXLE NUMBER	1	2	3	1	2	3
	HEAVIEST AXLELOAD ON					
DESCRIPTION	OUTSIDE AXLE			MIDDLE AXLE		
Beginning Axleload	8	15	31	8	31	15
Incremental Axleload	0	+2	-2	0	-2	+2
Final Axleload	8	21	25	8	25	21
Beginning Axleload	12	13	29	12	29	13
Incremental Axleload	0	+2	-2	0	-2	+2
Final Axleload	12	19	23	12	23	19
Beginning Axleload	16	11	27	16	27	11
Incremental Axleload	0	+2	-2	0	-2	+2
Final Axleload	16	17	21	16	21	17
Beginning Axleload	20	9	25	20	25	9
Incremental Axleload	0	+2	-2	0	-2	+2
Final Axleload	20	15	19	20	19	15
	Equal Tandem					
Beginning Axleload	2	26	26			
Incremental Axleload	+2	-1	-1			
Final Axleload	24	15	15			

TABLE 4. COEFFICIENTS FROM REGRESSION ANALYSES OF UNEQUAL LOAD DISTRIBUTION ON INDIVIDUAL AXLES OF TRIDEM AXLE GROUP

$$\log(\text{Multiplying Factor}) = a + b(\text{Ratio}) + c(\text{Ratio})^2$$

in which Ratio = (M - L) / I

M = Maximum Axleload, kips,
I = Intermediate Axleload, kips,
L = Least Axleload, kips, and
a,b,c = coefficients

Load Pattern: 1. L,I,M 2. M,I,L 3. M,E,E 4. E,E,M	
Constant a	0.468782731
Coefficient b	1.093207072
Coefficient c	-0.1503124207
Standard Error of Estimate	0.073149
Correlation Coefficient, R	0.96024
F Ratio	1183.4
Sample Size	648
Load Pattern: 1. I,L,M 2. M,L,I 3. E,L,E	
Constant a	-0.1161216122
Coefficient b	1.507954095
Coefficient c	0.377814882
Standard Error of Estimate	0.069341
Correlation Coefficient, R	0.92765
F Ratio	326.9
Sample Number	343
Load Pattern: 1. L,M,I 2. I,M,L 3. E,M,E	
Constant a	-0.0235937584
Coefficient b	1.283412872
Coefficient c	-0.2187655038
Standard Error of Estimate	0.088165
Correlation Coefficient, R	0.92395
F Ratio	710.7
Sample Size	478
Load Pattern: 1. L,E,E 2. E,E,L	
Constant a	0.0004399421
Coefficient b	0.8053052125
Coefficient c	0.2363591702
Standard Error of Estimate	0.05634
Correlation Coefficient, R	0.96827
F Ratio	1037.4
Sample Size	282
Load Pattern: All Patterns Above	
Constant a	-0.198429071
Coefficient b	1.20191282
Coefficient c	-0.1746353238
Standard Error of Estimate	0.09792
Correlation Coefficient, R	0.9240
F Ratio	2085.4
Sample Size	1951

TABLE 5. FATIGUE ANALYSES OF WEIGHT DATA ON TRIDEMS OF SINGLE-FRAME VEHICLES OR TRACTORS OF SEMI-TRAILER VEHICLES, ALL AXLES

	SUM OF EAL	UNEVEN / EVEN
Fatigue for Evenly Loaded Tridem	503.70	
Adjusted Fatigue by Load Pattern	1256.75	2.4950
Adjusted Fatigue without Regard to Load Pattern	1170.86	2.3245
Total Number of Tridems Analyzed	1,951	
Fatigue for Evenly Loaded Tandem	104.76	
Adjusted Fatigue for Unevenly Loaded Tandem	3419.50	32.64
Total Number of Tridems Analyzed as Tandems	19	

E = All Axles Evenly Loaded
M = Heaviest Axleload of Tridem
L = Least Axleload of Tridem
I = Intermediate Axleload of Tridem

LOAD PATTERN ON TRIDEM	NUMBER ANALYZED	PERCENT
E,E,E	200	10.3
M,E,E	71	3.6
E,M,E	13	0.7
E,E,M	74	3.8
L,E,E	170	8.7
E,L,E	31	1.6
E,E,L	112	5.7
L,I,M	299	15.3
L,M,I	355	18.2
I,L,M	119	6.1
I,M,L	110	5.6
M,L,I	193	9.9
M,I,L	204	10.5
Total	1,951	100.0

TABLE 6. FATIGUE ANALYSES OF WEIGHT DATA ON TRIDEMS OF SINGLE-FRAME VEHICLES OR TRACTORS OF SEMI-TRAILER VEHICLES, AXLES 2, 3, AND 4

	SUM OF EAL	UNEVEN / EVEN
Fatigue for Evenly Loaded Tridem	287.65	
Adjusted Fatigue by Load Pattern	839.31	2.9178
Adjusted Fatigue without Regard to Load Pattern	757.24	2.6325
Total Number of Tridems Analyzed	1,055	
Fatigue for Evenly Loaded Tandem	2.53	
Adjusted Fatigue for Unevenly Loaded Tandem	82.66	32.67
Total Number of Tridems Analyzed as Tandems	11	

E = All Axles Evenly Loaded
M = Heaviest Axleload of Tridem
L = Least Axleload of Tridem
I = Intermediate Axleload of Tridem

LOAD PATTERN ON TRIDEM	NUMBER ANALYZED	PERCENT
E,E,E	77	7.3
M,E,E	24	2.3
E,M,E	4	0.4
E,E,M	38	3.6
L,E,E	120	11.4
E,L,E	4	0.4
E,E,L	71	6.7
L,I,M	227	21.5
L,M,I	309	29.3
I,L,M	16	1.5
I,M,L	42	4.0
M,L,I	21	2.0
M,I,L	102	9.6
Total	1,055	100.0

TABLE 7. FATIGUE ANALYSES OF WEIGHT DATA ON TRIDEMS OF SINGLE-FRAME VEHICLES OR TRACTORS OF SEMI-TRAILER VEHICLES, AXLES 4, 5, AND 6

	SUM OF EAL	UNEVEN / EVEN
Fatigue for Evenly Loaded Tridem	216.05	
Adjusted Fatigue by Load Pattern	417.44	1.93
Adjusted Fatigue without Regard to Load Pattern	413.62	1.91
Total Number of Tridems Analyzed	896	
Fatigue for Evenly Loaded Tandem	102.23	
Adjusted Fatigue for Unevenly Loaded Tandem	3336.84	32.64
Total Number of Tridems Analyzed as Tandems	8	

E = All Axles Evenly Loaded
M = Heaviest Axleload of Tridem
L = Least Axleload of Tridem
I = Intermediate Axleload of Tridem

LOAD PATTERN ON TRIDEM	NUMBER ANALYZED	PERCENT
E,E,E	123	13.7
M,E,E	47	5.3
E,M,E	9	1.0
E,E,M	36	4.0
L,E,E	50	5.6
E,L,E	27	3.0
E,E,L	41	4.6
L,I,M	72	8.0
L,M,I	46	5.1
I,L,M	103	11.5
I,M,L	68	7.6
M,L,I	171	19.2
M,I,L	102	11.4
Total	896	100.0

TABLE 8. PERCENTAGE OF TRIDEMS WITH MIDDLE AXLE AS PART OF GIVEN LOAD PATTERN

LOAD PATTERN	PERCENTAGE
x,M,x	24.5
x,L,x	17.6
x,I,x	25.8
x,E,x	32.1
Total	100.0

TABLE 9. REGRESSION COEFFICIENTS TO CALCULATE ADJUSTMENT FACTORS FOR VARYING TIRE PRESSURES AND AXLE CONFIGURATIONS FOR EQUALLY DISTRIBUTED TIRE LOADS

$$\log(\text{Factor}) = A + B*\log(\text{TCP}) + C*(\log(\text{TCP}))^2$$

Where TCP = Tire Contact Pressure

THICKNESS OF ASPHALTIC CONCRETE (inches)	COEFFICIENTS A	B	C
	FOUR-TIRED SINGLE AXLE		
3	-2.464465	0.576804	0.420942
4	-1.962926	0.591450	0.263080
5	-1.637979	0.612273	0.154626
6	-1.414034	0.635424	0.075089
7	-1.253849	0.659304	0.014209
8	-1.136684	0.683179	-0.033811
9	-1.049978	0.706696	-0.072534
10	-0.985633	0.729684	-0.104286
	EIGHT-TIRED TANDEM AXLES		
3	-2.573477	0.647141	0.414958
4	-2.221248	0.803333	0.224419
5	-1.889261	0.818996	0.116696
6	-1.579889	0.763381	0.054667
7	-1.291573	0.668360	0.020454
8	-1.022015	0.550498	0.004322
9	-0.768984	0.419143	0.000498
10	-0.530517	0.279885	0.005342
	TWELVE-TIRED TRIDEM AXLES		
3	-2.640784	0.686070	0.413835
4	-2.224371	0.777724	0.239410
5	-1.829865	0.730261	0.147497
6	-1.461152	0.614593	0.100533
7	-1.116870	0.462852	0.080565
8	-0.794540	0.291453	0.077889
9	-0.491654	0.109482	0.086793
10	-0.205964	-0.077749	0.103706

TABLE 10. REGRESSION COEFFICIENTS TO CALCULATE ADJUSTMENT FACTORS FOR VARYING TIRE PRESSURES AND AXLE CONFIGURATIONS FOR EQUALLY DISTRIBUTED TIRE LOADS

$$\log(\text{Adjustment Factor}) = A + B*\log(TCP) + C*(\log(TCP))^2$$

Where TCP = Tire Contact Pressure

THICKNESS OF ASPHALTIC CONCRETE (inches)	COEFFICIENTS A	B	C
		TWO-TIRED SINGLE AXLE	
3	-11.423641	8.452615	-1.206807
4	-9.718723	7.272744	-1.071370
5	-8.667064	6.604668	-1.020443
6	-7.983404	6.219065	-1.013936
7	-7.528589	6.005482	-1.033063
8	-7.225865	5.903743	-1.067872
9	-7.029159	5.878171	-1.112632
10	-6.909049	5.906263	-1.163835
		FOUR-TIRED TANDEM AXLES	
3	-11.983535	8.850933	-1.257276
4	-10.133166	7.527803	-1.086909
5	-9.191001	6.946769	-1.050864
6	-8.721212	6.741902	-1.079290
7	-8.540266	6.763541	-1.145226
8	-8.543689	6.926599	-1.233377
9	-8.670125	7.181627	-1.335045
10	-8.881250	7.498079	-1.444985
		SIX-TIRED TRIDEM AXLES	
3	-12.227565	9.069919	-1.304090
4	-10.347085	7.708593	-1.121828
5	-9.423848	7.141287	-1.087605
6	-9.016720	6.994653	-1.129134
7	-8.913110	7.093011	-1.213003
8	-9.009383	7.342882	-1.321764
9	-9.230684	7.690169	-1.445523
10	-9.539068	8.101609	-1.578329

TABLE 11. ADJUSTMENT FACTORS FOR TIRE INFLATION PRESSURES

AXLE LOCATION	AVERAGE CONTACT PRESSURE, PSI	ADJUSTMENT FACTOR
Steering	94.7	2.0202
Four-Tired Single	91.3	1.2393
Eight-Tired Tandem	91.3	1.2508
Twelve-Tired Tridem	91.3	1.2590

Tire Contact Pressure = 0.9*Inflation Pressure
1 PSI = 6,894.8 Pa

TABLE 12. COMPARISON OF AVERAGE DAMAGE FACTORS FOR VARIOUS VEHICLE CLASSIFICATIONS

VEHICLE CODE	AASHTO DAMAGE FACTOR	KENTUCKY METHODS A	KENTUCKY METHODS B	KENTUCKY METHODS C
CARS*	0.0020	0.0050	0.0050	0.0050
22	0.1981	0.2082	0.2082	0.3212
23	0.1174	0.3410	0.4668	0.8432
24**	0.1185	0.3410	0.4668	0.8443
321	0.3989	0.4501	0.4501	0.7226
322	0.4372	0.4673	0.4852	0.7584
332	1.1663	0.7735	0.9609	1.4272
333	0.8594	0.7126	0.7401	1.2481
5212	2.0302	1.8785	1.8785	2.5553
6312	1.2779	1.1330	1.1984	1.6292

Method A Includes No Adjustments.
Method B Includes Adjustments for Uneven Load Distribution and Axle Spacing Only.
Method C Includes Method B Plus Adjustments for Tire Contact Pressure.
*Cars Plus Others not Specifically Included.
**No Data for This Category on Loadometer Tape -- Assumed to be the Same as for "23" in These Analyses.

Vehicle Code
"22" = Two-axle truck, six tires
"23" = Three-axle single-frame truck, 10 tires
"24" = Four-axle single-frame truck, 14 tires
"321" = Three-axle semi-trailer truck having three single axles
"322" = Four-axle semi-trailer truck having two single axles and one tandem axle group
"332" = Five-axle semi-trailer truck having one single and two tandem axle groups
"337" = Five-axle semi-trailer truck having one single axle and one tandem axle group on the tractor and a tandem group having spread axles on the trailer
"333" = Six-axle semi-trailer truck having one single axle and one tandem axle group on the tractor and one tridem axle group
"5212" = Five-axle combination consisting of one tractor, with two single axles and one semi-trailer with one single axle followed by a full trailer with two single axles
"6313" = Six-axle combination consisting of a tractor with a single axle and one tandem axle group and one semi-trailer with one single axle followed by a full trailer with two single axles

TABLE 13. FATIGUE CALCULATIONS FOR "DOUBLE-BOTTOM" TRUCKS COMPARED TO FIVE-AXLE SEMI-TRAILER TRUCKS

	DOUBLE-BOTTOM TRUCK			FIVE-AXLE SEMI-TRAILER		
	GROSS	DAMAGE FACTORS		GROSS	DAMAGE FACTORS	
VEHICLE NUMBER	LOAD, KIPS	AASHTO	'81 KY	LOAD, KIPS	AASHTO	'81 KY
1	74.8	3.4524	3.9200	74.9	1.9314	2.0968
2	52.1	0.6943	0.7397	52.1	0.4523	0.4993
3	73.0	3.2530	3.7474	73.0	1.8180	1.5378
4	63.2	1.5343	1.5191	63.0	1.0347	1.0059
5	66.3	1.7517	1.5849	66.3	1.3235	1.2880
6	68.9	2.6632	2.8002	69.0	1.4038	1.3980
7	78.3	3.5905	3.7275	78.3	2.4021	2.1119
8	63.6	1.4319	1.3033	63.6	1.0089	0.7173
9	57.4	0.9610	0.9143	57.5	0.8545	0.7702
10	57.7	0.9271	0.8896	57.9	0.7252	1.0050
11	53.2	0.6758	0.6937	53.3	0.4926	0.4887
12	52.4	0.6801	0.6784	52.5	0.4836	0.4519
13	69.2	2.1202	1.9713	69.1	1.5433	1.2892
14	58.4	1.0750	1.0466	58.4	0.9884	0.8808
15	57.7	0.9921	0.9791	57.9	0.7252	1.0050
16	55.6	0.8821	0.8989	55.8	0.6143	1.0534
17	66.7	2.0937	2.0425	66.8	1.3998	1.0909
18	53.5	0.7387	0.7563	53.5	0.5680	0.4455
19	81.0	3.7338	3.9503	80.7	2.5560	2.3570
20	51.8	0.7001	0.7624	51.9	0.4436	0.5629
21	75.7	3.1153	3.1272	75.6	2.0570	1.5125
22	63.1	1.8607	1.9355	63.0	1.0167	1.1788
23	71.9	2.8771	3.1460	71.9	1.6849	1.4980
24	58.3	0.9939	0.9480	58.4	0.9884	0.8808
25	51.3	0.6021	0.6220	51.1	0.4128	0.4123
26	75.2	3.2352	3.5540	76.5	2.1554	1.7250
27	76.4	3.0525	3.1171	76.5	2.1554	1.7250
28	66.8	2.9656	3.4525	66.9	1.2514	1.2067
29	70.5	2.5926	2.7276	70.5	1.5037	1.2829
30	31.0	0.1035	0.2127	31.3	0.0837	0.1948
31	52.2	0.9870	0.7933	52.2	0.4500	0.4228
32	43.3	0.3810	0.4604	43.2	0.2701	0.3463
33	77.0	3.4345	3.6330	77.1	2.1418	1.5747
Average		1.8228	1.8961		1.1762	1.0885

AASHTO 1.8228 / 1.1762 = 1.5497
'81 KY 1.8961 / 1.0885 = 1.7419

TABLE 14. FATIGUE HISTORY DATA FOR CASE HISTORY

VEHICLE CODE	VOLUME	AASHTO EAL	EAL BY KENTUCKY METHOD A	B	C
CARS*	1,659,946	3,319.9	8,299.7	8,299.7	8,299.7
22	82,737	15,331.2	17,225.8	17,225.8	17,225.8
23	8,684	2,056.4	2,961.3	4,053.7	7,322.7
24	4,284	1,014.4	1,460.8	1,999.7	3,716.9
321	15,220	6,071.3	6,850.6	6,850.6	10,997.6
322	22830	9,981.3	10,668.5	11,077.1	17,493.5
332	506,630	579,584.7	391,878.3	486,820.8	717,981.8
337	19	27.9	18.4	23.5	33.8
333	2,962	2,559.2	2,110.8	2,192.2	3,696.8
5212	22,490	45,659.2	42,247.4	42,247.4	57,469.7
6312	575	734.8	651.4	668.3	936.7
Total	2,687,154	662,522.1	484,373.0	581,458.8	845,175.0

Kentucky EAL / AASHTO EAL = 845,175.0 / 662,522.1 = 1.2757

Kentucky Method:
- A = Includes No Adjustments.
- B = Includes Adjustments for Uneven Load Distribution and Axle Spacing Only.
- C = Includes Method B Plus Adjustments for Tire Contact Pressure.

*Cars Plus Others not Specifically Included.

TABLE 15. COMPARISON OF DAMAGE FACTORS

VEHICLE CODE	AXLE TYPE NUMBER	AASHTO DAMAGE FACTOR	KENTUCKY METHODS A	KENTUCKY METHODS B	KENTUCKY METHODS C
CARS*		0.0020	0.0050	0.0050	0.0050
22	1	0.0171	0.0810	0.0810	0.0810
	2	0.1010	0.1272	0.1272	0.1272
	Total	0.1981	0.2082	0.2082	0.2082
23	1	0.1130	0.3371	0.3371	0.6810
	3	0.0044	0.0039	0.1297	0.1622
	Total	0.1170	0.3410	0.4668	0.8432
24	1	0.1130	0.3371	0.3371	0.6810
	4	0.0055	0.0039	0.1297	0.1633
	Total	0.1185	0.3410	0.4668	0.8443
321	1	0.0621	0.2110	0.2110	0.4263
	2	0.2334	0.1675	0.1675	0.2076
	2	0.1034	0.0716	0.0716	0.0887
	Total	0.3989	0.4501	0.4501	0.7226
322	1	0.0581	0.2005	0.2005	0.4051
	2	0.3242	0.2424	0.2424	0.3004
	3	0.0549	0.0244	0.0423	0.0529
	Total	0.4372	0.4673	0.4852	0.7584
332	1	0.0893	0.2798	0.2798	0.5653
	3	0.5598	0.2648	0.3327	0.4161
	3	0.4949	0.2289	0.3484	0.4358
	Total	1.1440	0.7735	0.9609	1.4272
333	1	0.1482	0.4190	0.4190	0.8465
	3	0.4227	0.1906	0.1744	0.2181
	4	0.2885	0.1030	0.1467	0.1835
	Total	0.8594	0.7126	0.7401	1.2481
5212	1	0.0939	0.2911	0.2911	0.5881
	2	0.6889	0.6017	0.6017	0.7457
	2	0.5750	0.4799	0.4799	0.5947
	2	0.3583	0.2721	0.2721	0.3372
	2	0.3141	0.2337	0.2337	0.2896
	Total	2.0302	1.8785	1.8785	2.5553
6312	1	0.0515	0.1830	0.1830	0.3697
	3	0.1540	0.0642	0.0936	0.1171
	2	0.6198	0.5268	0.5628	0.6975
	2	0.0097	0.0096	0.0096	0.0119
	2	0.4429	0.3494	0.3494	0.4330
	Total	1.2779	1.1330	1.1984	1.6292

Axle Type Number:
- 1 = Two-Tired Steering Axle
- 2 = Four-Tired Single Axle
- 3 = Eight-Tired Tandem Axle
- 4 = Twelve-Tired Tridem Axle

Kentucky Method:
- A = Includes No Adjustments.
- B = Includes Adjustments for Uneven Load Distribution and Axle Spacing Only.
- C = Includes Method B Plus Adjustments for Tire Contact Pressure.

*Cars Plus Others not Specifically Included.

TABLE 16. VOLUMES OF FIVE VEHICLE CLASSIFICATIONS CONVERTED TO PERCENTAGES FOR 1964 AND 1984

	1964		1984	
VEHICLE CODE	NUMBER OBSERVED	PERCENTAGE	NUMBER OBSERVED	PERCENTAGE
22	3,543	32.35	82,737	13.01
23	110	1.00	8,684	1.37
321	972	8.87	15,220	2.39
322	3,821	34.89	22,830	3.59
332	2,507	22.89	506,630	79.64
Total	10,953	100.00	636,101	100.00

TABLE 17. COMPARISON OF VEHICLE USEAGE AND AVERAGE DAMAGE FACTORS, 1964 VERSUS 1984

	1964*			1984		
VEHICLE CODE	NUMBER	AVERAGE DAMAGE FACTOR	EAL	NUMBER	AVERAGE DAMAGE FACTOR	EAL
22	323,500	0.1724	55,771.4	130,100	0.2082	27,086.8
23	10,000	0.2079	2,079.0	13,700	0.8432	11,551.8
321	88,700	1.1075	98,235.3	23,900	0.7226	17,270.1
322	348,900	0.6873	239,799.0	35,900	0.7584	27,226.6
332	228,900	0.4018	91,972.0	796,400	1.4272	1,136,622.1
Total	1,000,000		487,856.7	1,000,000		1,219,757.4

*Tire Contact Pressure = 67.5 psi (465 kPa)
1984 / 1964 : 1,219,757.4 / 487,856.7 = 2.5002